AD-759 270

FKCOMB, A FAST GENERAL-PURPOSE ARRAY PROCESSOR

E. Smart

Teledyne Geotech

Prepared for:

Advanced Research Projects Agency
Air Force Technical Applications Center

20 December 1972

........contributing to man's
understanding of the environment world

FKCOMB, A FAST GENERAL-PURPOSE ARRAY PROCESSOR

E. SMART
SEISMIC ARRAY ANALYSIS CENTER

20 DECEMBER 1972

Prepared for
AIR FORCE TECHNICAL APPLICATIONS CENTER
Washington, D.C.

Under
Project VELA UNIFORM

Sponsored by
ADVANCED RESEARCH PROJECTS AGENCY
Nuclear Monitoring Research Office
ARPA Order No.1620

TELEDYNE GEOTECH
ALEXANDRIA LABORATORIES

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FKCOMB, A FAST GENERAL-PURPOSE ARRAY PROCESSOR

SEISMIC ARRAY ANALYSIS CENTER REPORT NO. 9

AFTAC Project Number:	VELA T/2709
Project Title:	Seismic Array Analysis Center
ARPA Order No.:	1620
ARPA Program Code No.:	2F10
Name of Contractor:	Teledyne Geotech
Contract No.:	F33657-72-C-0471
Effective Date of Contract:	1 January 1972
Amount of Contract:	$1,663,848
Contract Expiration Date:	30 June 1973
Project Manager:	Harry Mack (703) 836-3882

P.O. Box 334, Alexandria, Virginia

Unclassified
Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY (Corporate author) Teledyne Geotech Alexandria, Virginia	2a REPORT SECURITY CLASSIFICATION Unclassified 2b GROUP

3 REPORT TITLE

FKCOMB, A FAST GENERAL-PURPOSE ARRAY PROCESSOR

4 DESCRIPTIVE NOTES (Type of report and inclusive dates)
Scientific

5 AUTHOR(S) (Last name, first name, initial)

Smart, E.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
20 December 1972	30	4

8a CONTRACT OR GRANT NO. F33657-72-C-0471 b. PROJECT NO. VELA T/2709 c ARPA Order No. 1620 d. ARPA Program Code No. 2F10	9a ORIGINATOR'S REPORT NUMBER(S) 9 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10 AVAILABILITY/LIMITATION NOTICES

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

11 SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Advanced Research Projects Agency Nuclear Monitoring Research Office Washington, D.C.

13 ABSTRACT

This report describes FKCOMB, a fast general-purpose array processing program which employs frequency-wavenumber analysis. A quasi-online long-period array processing package has been designed around FKCOMB for use at the Seismic Array Analysis Center. The input parameters required for operating the program are described.

14 KEY WORDS
Frequency-wavenumber
Arrays
Processing

1473

Unclassified
Security Classification

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INTRODUCTION

Frequency-wavenumber (f-k) spectral estimation is a powerful technique for signal detection and waveform analysis of digitally recorded array data. The f-k spectrum of a given segment of array output is the squared modulus of the multidimensional Fourier transform of the data in time and space. The f-k spatial representation of a propagating wave is shown schematically in Figure 1. Using discrete Fourier analysis in the time dimension, the representation can be thought of as a series of layers normal to the frequency axis, each layer representing the wavenumber plane at a given frequency. The wave is thus represented as a series of power maxima in the layers, and the locus of these maxima is determined by the phase velocity of the wave (for discussion, Smart 1971).

The advantage of this process is that propagating wave components are easily recognized and separated from one another, subject to the limitations imposed by the array geometry, sensor weighting, and the type of spectral smoothing employed. In essence, f-k analysis is beamforming in the frequency domain. The method takes advantage of the fact that the signal-to-noise ratio varies with frequency, so the beamforming is done frequency by frequency. Also, by staying in the frequency domain a great many beams can be examined rapidly, the number being limited only by the resolution cell of the array response. In practice this means that the azimuth and velocity of a signal need not be assumed: one merely accepts the beam with maximum power. This fact is important for signals such as long-period seismic surface waves, which not only are dispersive, i.e., their phase velocity varies with frequency but whose arrival azimuth may also vary with frequency due to lateral inhomogeneities in the earth.

FKCOMB is a fast f-k analysis program which was used in an automatic processing system for microbarograph array data (Smart and Flinn, 1971). It has been incorporated into the SAAC long-period processing package for quasi-online processing of ALPA, LASA, and NORSAR long-period seismic data (Mack, 1972).

GENERAL DESCRIPTION OF FKCOMB

FKCOMB is a software system which uses f-k analysis for continuous processing of time-varying data from arrays of sensors. The output is in the form of a bulletin which lists signal detections and gives their phase velocity, arrival azimuth, signal power, signal-to-noise ratio, and F statistic (related to signal-to-noise ratio; see Smart and Flinn, 1971) as a function of frequency and arrival time. The processor is shown schematically in Figure 2. An initial time window is specified. The multichannel data in this window are deglitched and automatically edited to delete dead or noisy traces. The data are then Fourier transformed in time and space. Maxima of power in three-dimensional f-k space are automatically picked, and if these maxima exceed a specified signal-to-noise detection threshold, and are within a specified phase velocity range, the maxima are listed together with the corresponding arrival azimuth, phase velocity, period, signal power estimate, signal-to-noise ratio, and F statistic. Two-dimensional maxima also occur; these are places which are maximum within a given wavenumber plane but not along the frequency axis. If such two-dimensional maxima satisfy the specified signal-to-noise ratio and phase velocity criteria, and if the corresponding approximation to group velocity (see below) is reasonable, then the maxima are also listed by the processor.

An option is available at this point to detect smaller signals which might be masked by the detected signals. In this option, the maximum power peaks and their associated sidelobes are removed by a filtering process referred to as 'stripping', and the secondary maxima are picked from the stripped data. If any of these secondary maxima satisfy the original detection criteria, their azimuth, etc., are also listed.

The time window is then shifted forward or backward in time by any specified amount, and the entire process (including editing) is repeated. A sample of the output listing is shown in Figure 3.

Data editing

After the data are despiked, the variance of each channel in the selected time window is calculated and the mean variance across channels is computed. Dead channels have very small variance after the mean is removed, and excessively noisy channels have a large variance. If a given channel variance is greater or smaller than the mean by a given factor (input parameter SLOP), that channel is discarded, the mean of the remaining channels is computed, and this process is repeated until the variances of the remaining channels all lie within the specified bounds. The discarded channel numbers are listed in the output bulletin for each time window.

The variances of the broad-band time domain data are used for editing rather than the variances of the individual frequency components for the following reason: two signals interfering in the area of the array yield spectral nulls in the data from certain sensors at certain frequencies. Hence a large variation in the variance of a particular frequency component can be due to a physically reasonable situation and not necessarily due to noisy or dead traces. Variations caused by wave interference are greatly reduced when the broad-band data are used instead.

Time gaps and time reversals

The multichannel data are normally analyzed as a series of overlapping time windows, the length of the windows and the amount of overlap being input parameters to the program. If a gap of one or two data samples occurs within a particular time window, then the last good value is repeated to fill up the gap, and the analysis continues. If the gap is more than two samples long, then the processor analyzes the last full window up to the data gap and the first full window after the gap, continuing routinely. This procedure is also used in case of a time reversal: the last full window before the reversal and the first full window after the start of correct time progression are used before the analysis continues. The program indicates on the output bulletin when data gaps or time reversals were detected, and gives the corrective procedure used.

The fast f-k analysis algorithm

The power at a given frequency and wavenumber is computed as:

$$P(f, \underline{k}) = \left| \frac{1}{N} \sum_{n=1}^{N} A_n(f) \exp[2\pi i(\phi_n(f) - \underline{k} \cdot \underline{r}_n)] \right|^2 \qquad (1)$$

where

f = frequency

$\underline{k}$ = vector wavenumber

N = number of data channels

n = sensor or channel index

$\underline{r}_n$ = vector location of the n'th sensor with respect to an arbitrary origin.

$A_n(f)\exp[2\pi i\phi_n(f)]$ = Fourier transform of the n'th data channel.

$A_n(f)$ is the amplitude part of the transform

$\exp[2\pi i\phi_n(f)]$ is the phase part of the transform in which $\phi_n(f)$ is the phase angle.

Expression (1) is evaluated for a matrix of wavenumber values at a series of discrete frequencies, as specified in the input parameters; it can be considered as a three-dimensional transform space with frequency being one dimension and the vector wavenumber $\underline{k}$ being the other two dimensions. For computation, $\underline{k}$ is resolved into a Cartesian coordinate system, with k_y related to geographic north and k_x related to geographic east.

A wavenumber value, say k_0, is related to the phase velocity V by:

$$V = f/k_0 \qquad (2)$$

Thus phase velocity is inversely proportional to the distance from the frequency axis. The locus of constant values of V is a cone in f-k space, with the apex at the point $f = k_x = k_y = 0$.

For f-k analysis we calculate the power at a matrix of wavenumber values separated by a grid interval $\Delta\underline{k}$. This is greatly speeded up by using the following relation:

$$A_n(f)\exp[2\pi i(\phi_n(f) - (\underline{k}+\Delta\underline{k}) \cdot \underline{r}_n)] \tag{3}$$

$$= A_n(f)\exp[2\pi i(\phi_n(f) - \underline{k}\cdot\underline{r}_n)]\exp[-2\pi i\Delta\underline{k}\cdot\underline{r}_n]$$

Thus if a set of N terms had been calculated for the first wavenumber value $\underline{k}_1$, the values at $\underline{k}_2 = \underline{k}_1 + \Delta\underline{k}$ are obtained merely by multiplying those terms by a factor $\exp(-2\pi i\ \underline{k}\cdot\underline{r}_n)$. Hence if a regular grid is used, only one set of kernels $\exp(-2\pi i\underline{k}_1\cdot\underline{r}_n)$ need be generated, the remaining values being obtained with successive multiplication by the invariant kernels $\exp(-2\pi i\ \Delta\underline{k}\cdot\underline{r}_n)$.

Initially a coarse wavenumber grid is used to obtain an approximate location for the power maximum; we discuss the selection of spacing below. Once a rough location for the first maximum has been obtained, an 'uphill walk' approach is used to determine the exact location of the peak. Beginning at the point of greatest power on the coarse grid, the program steps out in a plane of constant frequency along each of the four cartesian coordinate directions to determine the direction in which the power is rising, and then continues to compute successive points in that direction as long as the power is rising. When the power begins to fall off in the direction being explored, a new direction is determined and followed, and the process is repeated until a place is reached where the four adjacent points in f-k space all show lower power. The grid spacing is then reduced by a factor of 6 and the same procedure is repeated to refine the location of the power maximum. The amount of computation required is about an order of magnitude less than would be required for computing and searching the complete two-dimensional spectral matrix.

All two-dimensional peaks located in this manner are then checked to see if they are also maxima in the frequency direction as well; such peaks are defined by:

$$\frac{\partial P}{\partial f} = \frac{\partial P}{\partial k_x} = \frac{\partial P}{\partial k_y} = 0$$

Of course, the extrema considered are just the maxima; minima are not of interest.

The program checks through the different frequencies as follows: consider the power in the wavenumber plane for the n'th frequency. The power maximum in this layer is compared with the power and location of the maximum in the (n-1)'th and (n+1)'th layers; for clarity of exposition we call the power at these peaks P_n, P_{n-1}, and P_{n+1}. If both P_{n+1} and P_{n-1} are smaller than P_n, then P_n is flagged as a three-dimensional maximum. If either P_{n+1} or P_{n-1} is greater than P_n, a check is made on the respective positions of the peaks in wavenumber space; suppose that $P_{n-1} > P_n$. The vector wavenumber separation between the location of P_n and the location of P_{n-1} is calculated, and the following logic is followed:

(a) The separation is less than half the width of the main lobe of the array response. In this case, the two peaks are presumed to be part of the same signal, and P_n is not designated as a three-dimensional maximum.

(b) The separation is greater than one halfwidth of the main lobe of the array response. In this case,

P_{n-1} is presumed to be part of another signal. To see whether P_n itself is nevertheless a three-dimensional maximum, the power is checked in the (n-1)'th and (n+1)'th layers at the same vector wavenumber as the peak P_n: suppose these are Q_{n-1} and Q_{n+1} respectively. Then P_n is designated as a three-dimensional peak if $P_n > Q_{n-1}$ and $P_n > Q_{n+1}$. This identification process is continued for all the frequency layers.

Wavenumber peaks which are two-dimensional but not three-dimensional, i.e., those for which

$$\frac{\partial P}{\partial k_x} = \frac{\partial P}{\partial k_y} = 0 \qquad , \qquad \frac{\partial P}{\partial f} \neq 0$$

may nevertheless appear in the bulletin, listed separately from the three-dimensional peaks. As a check on the validity of the two-dimensional peaks, a group velocity check is made, as follows. The values of $\Delta f/\Delta k$ are calculated for each peak and listed in the bulletin, where Δf is the frequency difference between adjacent layers and Δk is the difference in wavenumber position of the maxima in the two adjacent layers. The ratio $\Delta f/\Delta k$ is a first-order approximation to the group velocity of a propagating signal; thus, if two-dimensional peak is representative of the power in a propagating signal at that given frequency, the approximate group velocity should have a reasonable value. A common cause of spurious two-dimensional peaks is leakage of power (due to the finite length of the time window) from a large peak in the spectrum. We have shown previously (Smart, 1971) that this leakage occurs along lines of constant wavenumber (i.e., $\Delta k = 0$), so the calculated approximation to group velocity $\Delta f/\Delta k$ will fall outside the normal range of group velocities expected for seismic signals (2 to 3 kilometer/second).

At each frequency, only the largest two-dimensional maximum is considered at first, in order to avoid picking power entering the array through sidelobes in the array response. After each peak is examined and either accepted or rejected as a signal detection, FKCOMB has the option of returning to the frequency section being examined, in order to consider secondary maxima. These smaller relative maxima may well be sidelobes of the leargest peak, and in fact, the whole section will be contaminated with power from that peak. Thus it is necessary to remove the largest peak, i.e., 'strip' it out, before proceeding with the anlaysis.

Thus, after a maximum in the n'th frequency section has been examined, it is removed by the stripping process (see below), along with its sidelobes, and the plane is searched for another power maximum. This peak is then subjected to the previously described comparison with the (n-1)'th and (n+1)'th layers both before and after they have themselves been stripped. If a detection is made after stripping, the fact is so indicated on the output bulletin. FKCOMB at present picks only the primary and one secondary peak at each frequency. Experience in using FKCOMB to analyze long-period seismic data has shown that signals are usually detected from the three-dimensional maxima, and the main interest in the two-dimensional peaks is to provide a more complete spectrum of the detected signal waveform.

The stripping process

The removal of the first signal peak and its associated sidelobes is achieved by subtracting an estimate of an appropriately phase-shifted complex signal from the complex Fourier transforms of the individual channels.

If a particular peak under consideration has a maximum at wavenumber $\underline{k}'$, the estimate of the signal at frequency f used in the stripping process is:

$$\frac{1}{N}\sum_{n=1}^{N} A_n(f)\exp[2\pi i(\phi_n(f) - \underline{k}'\cdot\underline{r}_n)] \tag{4}$$

This estimate is removed from the Fourier transform set by subtracting it from each of the transforms phase-shifted to $\underline{k}'$ and then shifting the remnant back to the origin in the wavenumber plane. The operation for the j'th data channel is thus:

$$\{A_j(f)\exp[2\pi i(\phi_j(f) - \underline{k}'\cdot\underline{r}_j)] - \frac{1}{N}\sum_{n=1}^{N} A_n(f)\exp[2\pi i(\phi_n(f) - \underline{k}'\cdot\underline{r}_n)]\}\exp(2\pi i\,\underline{k}'\cdot\underline{r}_j) \tag{5}$$

From these N filtered transforms a new wavenumber spectrum is computed, and its largest maximum is taken as the second pick at the frequency under consideration, to be accepted or rejected using the same criteria as were applied to the first pick.

This filtering scheme is based on two assumptions: first, that the signal is a plane wave, although slight departures from this condition are not significant, especially when the wavelength is of the same order as the array diameter. Second, that the spatial envelope for the propagating waves is approximately flat over distances equal to the size of the array, so that the spatial spectral smoothing function is simply the array response to a plane wave whose phase velocity is infinite and whose waveform is an impulse.

The latter assumption bears on the procedure of subtracting the mean Fourier transform from each of the N individual channel frequency transforms, for in doing that we are in effect subtracting the complex array response from the wavenumber transform, and thus removing not only the signal peak but also all its associated sidelobes.

The second wavenumber spectrum can be expressed as:

$$\underline{P}_2(f,\underline{k}) = \Big|\frac{1}{N}\sum_{j=1}^{N}\{A_j(f)\exp[2\pi i(\phi_j(f) - \underline{k}'\cdot\underline{r}_j)]$$

$$- \frac{1}{N}\sum_{n=1}^{N}A_n(f)\exp[2\pi i(\phi_n(f) - \underline{k}'\cdot\underline{r}_n)]\} \tag{6}$$

$$\cdot \exp[2\pi i\underline{k}'\cdot\underline{r}_j]\exp[-2\pi i\underline{k}\cdot\underline{r}_j]\Big|^2$$

or alternatively:

$$= \left| \frac{1}{N} \sum_{j=1}^{N} A_j(f) \exp[2\pi i(\phi_j(f) - \underline{k}\cdot\underline{r}_j)] \right.$$

$$- \frac{1}{N} \sum_{p=1}^{N} \{ [\frac{1}{N} \sum_{n=1}^{N} A_n(f) \exp[2\pi i(\phi_n(f) - \underline{k}'\cdot\underline{r}_n)] \qquad (7)$$

$$\left. \cdot \exp[2\pi i \underline{k}'\cdot\underline{r}_p] \} \exp[-2\pi i \underline{k}\cdot\underline{r}_p] \right|^2$$

The squared modulus of the difference between the two complex terms between the vertical bars is the estimate of the wavenumber spectrum that would be calculated if the signal at $\underline{k}'$ were not present.

The term to the left of the minus sign is the original unfiltered complex wavenumber spectrum. The expression in square brackets to the right is a constant transform, invariant from channel to channel. Thus the entire term to the right of the minus sign is simply a complex array response multiplied by the amplitude

$$\left| \frac{1}{N} \sum_{n=1}^{N} A_n(f) \exp[2\pi i(\phi_n(f) - \underline{k}'\cdot\underline{r}_n)] \right| \qquad (7a)$$

of the signal estimate at frequency f, and phase-shifted by an amount

$$\tan^{-1} \frac{\sum_{n=1}^{N} A_n(f)\sin[\phi_n(f) - \underline{k}'\cdot\underline{r}_n]}{\sum_{n=1}^{N} A_n(f)\cos[\phi_n(f) - \underline{k}'\cdot\underline{r}_n]} \tag{7b}$$

which is the phase angle of the signal estimate, all offset an amount $\underline{k}'$ from the origin in the wavenumber plane.

The assumption that the spatial envelope is flat is reasonable when considering long-period surface waves as recorded at ALPA, LASA, and NORSAR, because at the periods of interest there are at most only two cycles of the signal within the dimension of the array for any data window. Variations in instrument response will, however, introduce an unknown contribution to the spatial spectral smoothing function and thus impose a limit on the capability of this stripping process to separate signals of very different amplitude. This limit would, of course, apply to any array processing technique which depended on having constant or at least known instrument responses.

An example of the application of the stripping process is shown in Figure 4. The program FKCOMB does not at present furnish contoured sections, but these are easily calculated, and are useful for illustrating the f-k analysis.

The particular example used here shows how a dominant coherent peak is stripped away along with its sidelobes, and on recomputing the spectrum in the same wavenumber plane, the smaller second peak emerges clearly.

Signal-to-noise ratio and F statistic

The signal-to-noise ratio is defined as:

$$S/N = \frac{P(f,\underline{k})}{Av(f) - P(f,\underline{k})}$$

where $P(f,\underline{k})$ is the power at the maximum peak, and is taken as the signal power estimate at frequency f. $A_v(f)$ is the average channel power (the power averaged over channels) at frequency f:

$$Av(f) = \frac{1}{N}\sum_{n=1}^{N} A_n(f)^{2}$$

This value is recalculated after stripping.

The F statistic is defined as:

$$\varepsilon_F = \frac{P(f,\underline{k})}{A_v(f) - P(f,\underline{k})} \cdot (N-1)$$

(Shumway, 1971). An interesting aspect of the F statistic is that it allows us to distinguish energy arriving in sidelobes of the array from energy in the main lobe. For a more detail discussion of the application of the F statistic to seismic signal detection see Blandford (1971); examples of the application to infrasonic array data processing are given by Smart and Flinn (1971).

Selection of grid spacing

As mentioned above, a coarse wavenumber grid is chosen initially in order to keep computing time to a minimum. However, the spacing must be fine enough to ensure that at least one point falls on a main lobe above the height of the largest sidelobe of the array response. For example, if the largest sidelobe of the array response has a peak 9 dB down from the maximum of the response, then the grid spacing has to be selected so that at least one point falls within the 9 dB contour of the main lobe for any signal in the velocity range of interest.

In the case of arrays where spatial aliasing is a problem (such as ALPA) the above condition must be qualified by specifying the largest sidelobe which may be expected to occur in the velocity and frequency range specified by the input parameters.

In the initial coarse-grid computation of the wavenumber spectrum FKCOMB employes an isosceles triangular grid because it requires fewer points and less computation time than does a square grid. Nevertheless, the convention has been adopted that users will specify the optimum square grid interval required for the given sensor array and FKCOMB will convert that to the corresponding isosceles triangular grid spacing. Both grid intervals, DKX and DKY, must be specified and they are equal.

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APPENDIX

FKCOMB used as the SAAC LP processor

As was mentioned in the introduction FKCOMB forms the heart of the SAAC LP processing package. The current version can be used directly on the following kinds of data.

1. LASA, NORSAR and ALPA long period data from both the SAAC lowrate and highrate tapes.

2. LASA short period from the highrate tapes.

3. TFSO long period data.

The input parameters are as follows:

1) MOTION, FOLLOW - FORMAT (2A8)

Enter VERTICAL for vertical motion
LONGITUDINAL for horizontal radial motion
TRANSVERSE for horizontal transverse motion
(FOLLOW merely takes up the extra letters).

2) SWITCH - FORMAT (I5)

Enter 0 for processing without stripping
1 for processing with stripping

3) INC - FORMAT (I5)

Sample interval between start of sequential data blocks. If this figure equals the number of samples used in a data window there is no overlap.

4) IST - FORMAT (I5)

Number of the lowest frequency

desired from the set of discrete frequencies (numbers increase with frequency).

5) ISP - FORMAT (I5)

Number of the highest frequency required.

NB The number of any particular frequency is calculated from the window length and the sampling rate.

6) KCOUNT - FORMAT (I5)

Number of data windows to be analyzed.

7) SLOP - FORMAT (F10.4)

Variance limit used in the editing state.

8) UNDER, TOP - FORMAT (2F10.4)

Minimum and maximum velocities of interest. FKCOMB only searches the k-plane inside the lowest velocity limit and only lists detections made between the limits.

9) GLOWER, GUPPER - FORMAT (2F10.4)

Lower and upper group velocity limits defining range over which two dimensional peaks are accepted.

10) FSMIN - FORMAT (F10.4)

Minimum Fisher statistic below which no peaks are listed as detections. Defined in the text.

11) DKX,DKY - FORMAT (2F10.6)

Wavenumber grid separation values, see text for discussion on how to compute these.

12) ANGLE - FORMAT (F10.4)

Sets the inclination of the axis of the cone to be searched in f-k space. Normally ANGLE is set to zero and the cone axis is the frequency axis.

13) NDAY, NHR, NMIN, NSEC, NTENTH, MDAY, MHR, MMIN, MSEC, MTENTH, ID, NYEAR - FORMAT (5I5, IOX, 5I5, 3X, A2, I5)

NDAY,...,NTENTH, is the day, hour, minute, second and decisecond of the start of the first data block.

MDAY,...,MTENTH, defines the end of the first block. All subsequent blocks will have the same length as the first.

ID defines the record type:

AL: ALPA
LA: LASA short period
LL: LASA long period
XW: NORSAR
TF: TFO

NYEAR is the calendar year in which the data were recorded. The year is not included in the data records and so this parameter does not affect the time search procedures.

14) NSMPLS, NCHLS, LEADER, NWORDS, NORMAL, NDP - FORMAT (6I10)

NSMPLS = number of sample times per data record.

NCHLS = number of channels the user wishes to retrieve.

LEADER = number of 2-byte words in the record before the first data word.

NWORDS = number of 2-byte words which one must pass in going from a given channel in one frame to the rest

NORMAL = the expected number of deciseconds between the start of sequential data records.

NDP = 5 if ID = XW, 0 otherwise. NSMPLS, LEADER, NWORDS, NORMAL and NDP are invariant for a particular ID. The required values are as follows:

NSMPLS	LEADER	NWORDS	NORMAL	NDP	ID
5	75	409	5	0	LA
10	20	131	100	0	LL
15	10	95	150	0	AL
10	22	153	100	5	XW
60	6	36	600	0	TF

15) IWORD(I), ARRAY(I), SENSOR(I), Y(I), X(I), I=1,NCHLS
- FORMAT (1X,I3,3X,A4,18X,A2,28X,F7.3,7X,F7.3)

IWORD(I) = sequence number of the I^{th} channel in a data frame

ARRAY(I),SENSOR(I)= are not used by the program but only serve to identify the array and sensor to the user

Y(I) = north coordinate of the I^{th} sensor

X(I) = east coordinate of the I^{th} sensor.

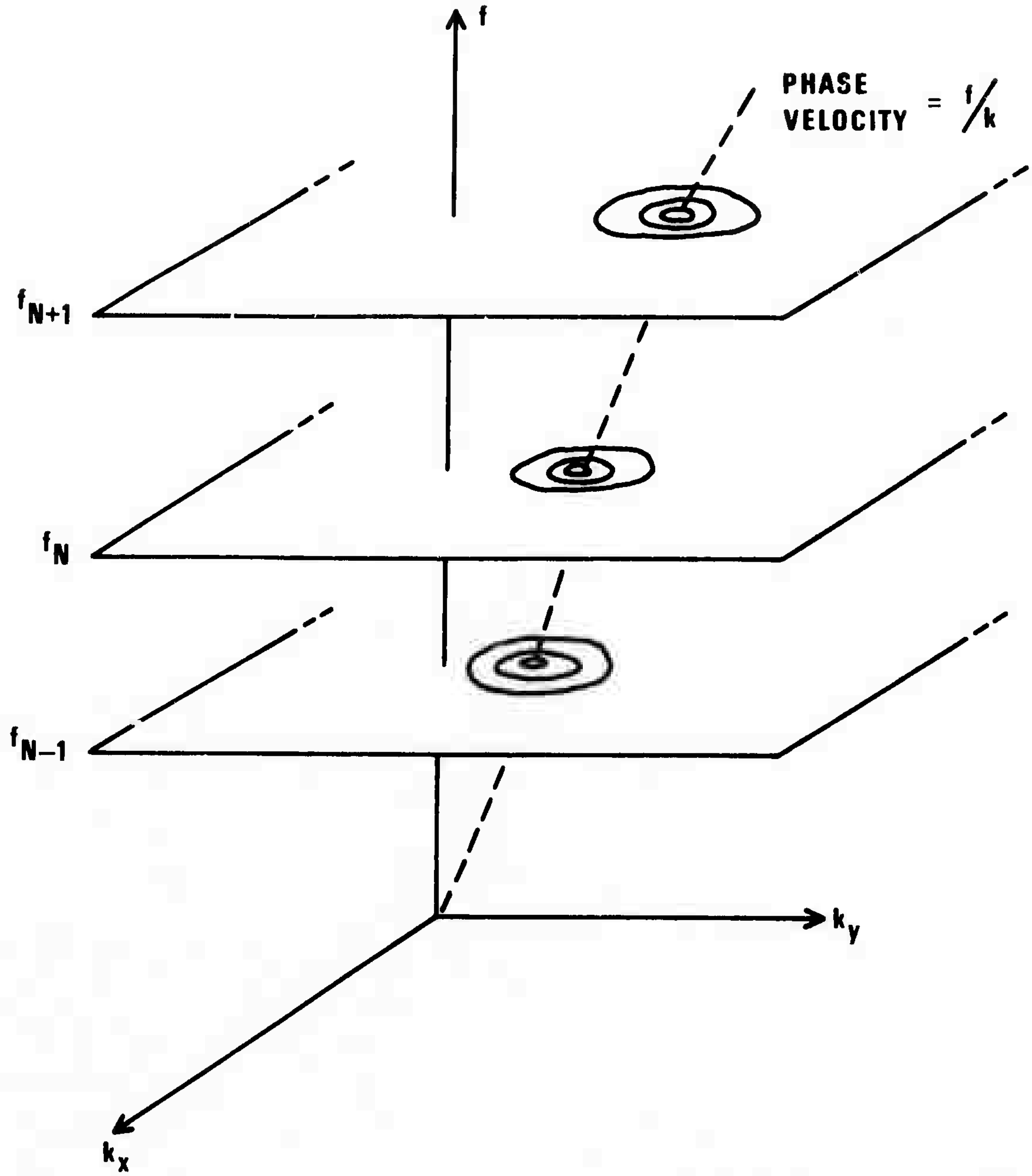

Figure 1. The frequency wavenumber representation of a propagating wave.

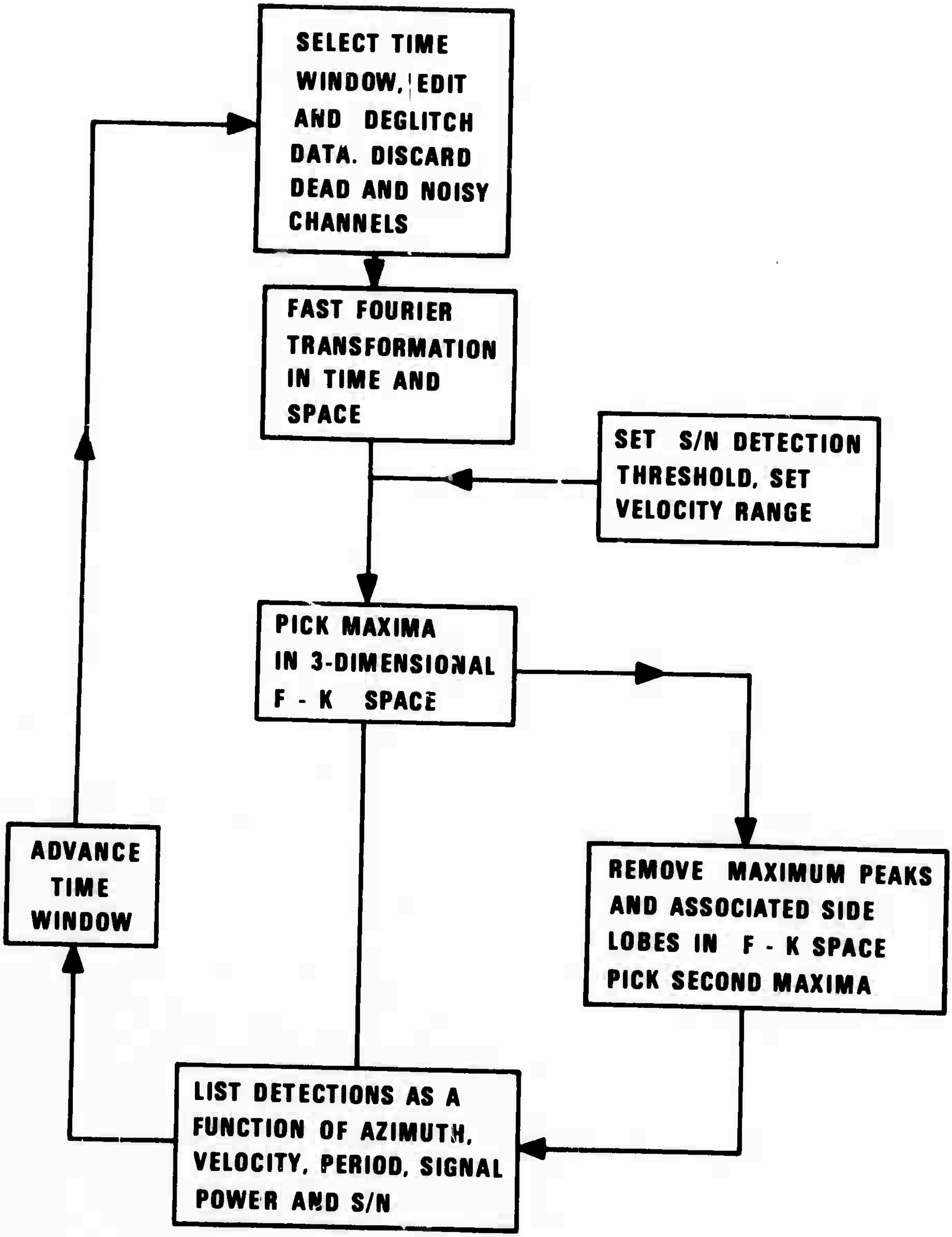

Figure 2. Schematic representation of the FKCOMB processor.

```
DATA RETRIEVAL STARTED AT 1034 GMT PLUS 36.0 SECONDS ON DAY 277.

DAY 277/1034 36.0 - 1038 51.0 GMT 1971
                                                              DROPPED CHANNELS  19 52
2-DIMENSIONAL MAXIMA
   9        0.6     4.06    358      32.0     0.184E 02                 0.0     3.79   0.1340E 00
  80        5.0     4.03    342      28.4     0.765E 02                 3.78   -0.94   0.3076E 00
   9        0.5     8.57    359      25.6     0.158E 02                -0.94    0.0    0.1555E 00
  52        3.3     3.20     63      23.3     0.427E 02                 0.0   -18.29   0.2807E 00
  31        1.9     5.02    219      23.3     0.857E 01    STRIPPED    -0.80    0.0    0.1258E 00
  33        2.0     3.55     58      21.3     0.458E 02               -18.29   14.01   0.3173E 00
  21        1.3     3.76     55      19.7     0.734E 02                14.01    0.0    0.4350E 00
  18        1.1     3.57     58      17.1     0.598E 02                 0.0     3.61   0.4531E 00
  14        0.9     3.49     17      17.1     0.250E 02    STRIPPED     0.0   -23.17   0.2928E 00
  68        4.3     3.57     59      16.0     0.453E 03                 3.61    3.97   0.1330E 01
  17        1.1     3.76     24      16.0     0.552E 02    STRIPPED   -21.95    0.0    0.4643E 00
3-DIMENSIONAL MAXIMA
  26 F-STATISTIC  1.6 S/N  6.40 K/S  10 DEGREES  34.1 SECONDS  0.430E 02                  0.1920E 00
  17        1.1     3.76     24      16.0     0.552E 02    STRIPPED                    0.4643E 00
  68        4.3     3.57     59      16.0     0.453E 03                                0.1330E 01
  52        3.2     3.60     62      19.0     0.145E 03                                0.6340E 00
   9        0.6     4.19     93      18.3     0.374E 02    STRIPPED                    0.3344E 00
  12        0.7     4.13    145      19.7     0.231E 02    STRIPPED                    0.2443E 00
  17        1.0     2.90    230      25.6     0.147E 02    STRIPPED                    0.1497E 00
  80        5.0     4.02    342      28.4     0.765E 02                                0.3076E 00

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                                                              DROPPED CHANNELS  19 52
2-DIMENSIONAL MAXIMA
  24        1.5    29.66    190      64.0     0.487E 02                -0.78    4.60   0.1090E 00
   8        0.5    14.20    134      51.2     0.271E 02                 4.60    0.0    0.1017E 00
  60        3.7     4.47    323      28.4     0.886E 02                 0.0     3.69   0.3310E 00
  73        4.6     4.38    325      25.6     0.134E 03                 3.69    0.0    0.4521E 00
  16        1.0     3.76    240      25.6     0.149E 02    STRIPPED     0.0     1.41   0.1507E 00
  11        0.7     3.27    232      23.3     0.100E 02                 0.0     7.31   0.1361E 00
  27        1.7     3.98    205      23.3     0.883E 01    STRIPPED     2.07    0.0    0.1277E 00
  12        0.8     3.42    221      21.3     0.551E 01                 7.31    0.0    0.1100E 00
   8        0.5     3.61     42      21.3     0.243E 01    STRIPPED     0.0    20.73   0.7313E-01
  42        2.7     3.85     66      19.7     0.468E 02                 0.0     1.83   0.3475E 00
 148        9.2     3.57     65      18.3     0.534E 03                 1.83    4.22   0.1264E 01
  33        2.1     3.61     52      17.1     0.197E 03                 4.22    2.14   0.8233E C0
  30        1.9     3.46     41      16.0     0.599E 02                 2.14 *******   0.4837E 00
3-DIMENSIONAL MAXIMA
   4 F-STATISTIC  0.2 S/N  4.10 K/S  22 DEGREES  42.7 SECONDS  0.113E 02  STRIPPED    0.7871E-01
  25        1.5     8.96     37      32.0     0.387E 02    STRIPPED                    0.1344E 00
 148        9.2     3.57     65      18.3     0.534E 03                                0.1264E 01
  10        0.6     4.05    195      17.7     0.349E 02    STRIPPED                    0.3346E 00
  22        1.4    18.60    235      56.9     0.518E 02                                0.1266E 00
  31        1.9     3.43    235      24.4     0.199E 02    STRIPPED                    0.1829E 00
  58        3.6    30.62    299      30.4     0.392E 02    STRIPPED                    0.1599E 00
 146        9.1     4.39    326      26.9     0.215E 03                                0.5441E 00
  15        0.9     3.88    356      17.1     0.456E 02    STRIPPED                    0.3959E 00
```

Figure 3. An example of the listed output. The word 'stripped' appears if the detection was made after stripping.

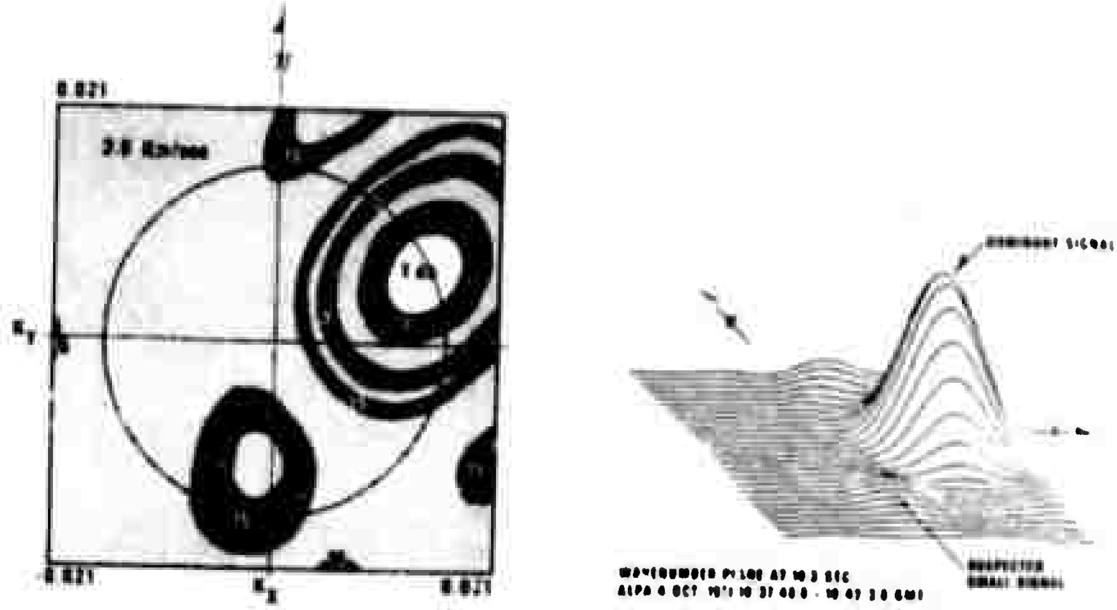

Figure 4a. Frequency wavenumber representation of time interfering signals. The wavenumber plane is shown on the left and a relief version is shown on the right.

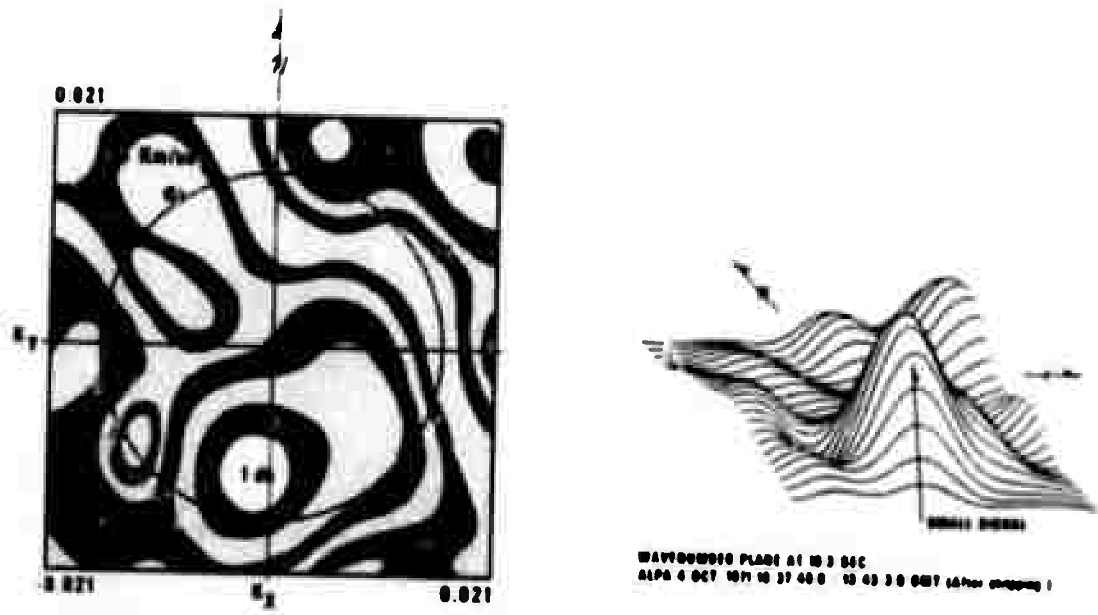

Figure 4b. Case shown above with dominant signal removed thereby enhancing the small signal. The right hand illustration is a relief version of the wavenumber plane shown on the left.